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# MOTION PERCEPTION. REPORT I. PERCEPTION OF MINUTE MOVEMENTS

A. Basler

Translation of "Uber das Sehen von Bewegungen. I. Mitteilung. Die Wahrnehmung kleinster Bewegungen," Pflügers Archiv für die Gesamte Physiologie, "Vol. 115, 1906, pp. 582-601

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16. Abstract The object of this study was to determine how small a displacement may be perceived as movement. Subjects observed minute displacements of a lever, mounted on a metal sheet and visible through a slit in a covering sheet. It was found that in the macula lutea a movement through a visual angle of 20 sec is perceived, even though two points less than 50 sec apart are not distinguished as separate. Subjects considerably overestimated minute movements, especially when the moving object was close to the eye. Motion perception decreases toward the periphery, most rapidly as one moves upward from the macula lutea. Speed of motion and total lighting also had an effect.

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# MOTION PERCEPTION. REPORT I. PERCEPTION OF MINUTE MOVEMENTS

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Although optical perception of motion has been the object of several physiological studies [1], usually only speed was considered, i.e., it was established how rapidly a body must be moved so that its change in location is directly perceived. /582*

However, little information is yet available concerning the relation between perceptibility and magnitude of the movement.

Consequently it appeared interesting to me to determine how small a displacement may be which is still perceptible, i.e., how far apart must be the two points between which the movement takes place.

## Method

In order to produce movements as small as possible the amplitude of which was still measurable, I constructed the following apparatus.

On a strong brass plate A (Fig. 1), a lever B is mounted, which can be turned around an axis F by means of a handle C. This rod is completely covered as far as the handle by another brass /583
plate D which is fastened to the first one.

In the second plate there is a gap E, 0.5 cm wide, located 2 cm from the axis F and perpendicular to the lever.

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* Numbers in the margin indicate pagination in the foreign text.

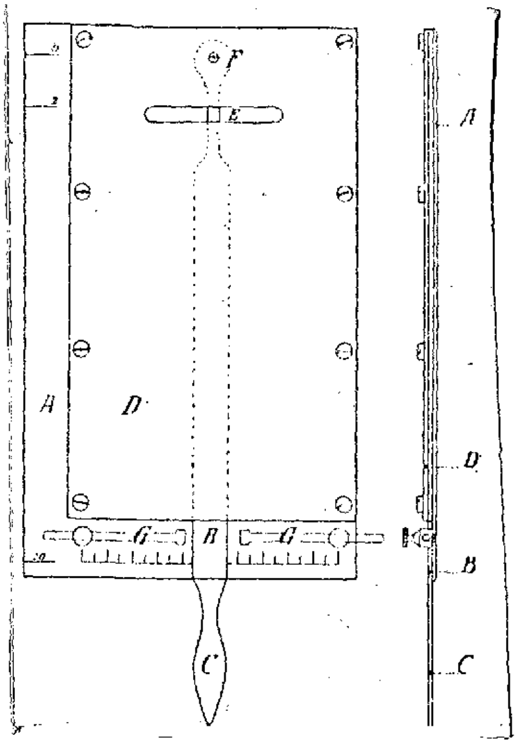

Fig. 1.

Below, where the rod projects out of the metal case, passing into the handle C, there is a millimeter scale. This scale is located 20 cm from the axis, or 10 times as far as the distance of the gap from the axis. Consequently, if the lever is moved 1 mm on the scale, then the displacement at the location of the gap is 0.1 mm.

Since with rapid movement the millimeter divisions cannot be read on the two end positions of the rod, two adjustable obstructions G are installed, by means of which the desired movement amplitude can be established at the outset.

The part of the lever which is visible in the fissure E is pasted over with white baryta paper, so that it stands out as well as possible from the support. Everything else is covered with black paper.

I conducted investigations with this apparatus in the following way.

The apparatus was fastened to a wall in such a way that the gap within which the movement took place was located 1.28 m above the floor.

The observer, whose head was fixed in a definite position by resting it in a support, took a position 2 m away from the /584
apparatus. He observed the white strips which were moved

rapidly back and forth by the conductor of the experiment by means of the lever. The experimentor determined and recorded the excursion of the movement, with the observer having no idea of the amplitude of movement or of what the experimentor expected. The subject merely had to report whether the strip moved or not, and in the first case, how large the excursion was estimated to be. Needless to say, many trick experiments were included.

The entire apparatus, except for the gap in which movement took place, was covered with black paper. It proved necessary to conceal the handle and the hand moving it by means of a covering of black cardboard, since these relatively large movements significantly interfered with correct observation of the much smaller movements of the white strip.

Since with the above-described apparatus each experiment required two persons, for the sake of simplicity I conducted my first observations with an optical distance of 30 cm. Consequently, although the resulting movement was small enough, I still had to alter the apparatus in such a way that the movable lever was replaced by a slat 1 m long. Here as well, the fissure was 2 cm from the axis and the scale 100 cm from the axis. Thus, the amplitude of the excursion perceived below the gap was 1/50th of the displacement on the scale. It was thus possible to produce a movement of 0.02 mm with fair precision, since the slat was moved 1 mm on the scale.

In front of the apparatus, which was placed by a window, sat the subject, supporting his head on a stand in such a way that the observing eye was precisely 30 cm from the moving paper strip.

This apparatus offered the advantage that the observer could himself produce the movement with his hand. In order to avoid suggestive effects here as well, I set down the amplitude of movement before each observation without looking at the scale, and only took a reading after I had recorded my evaluation.

All the observations were made by me (designated in the protocols as B) and by another person (N). The experiments were conducted partly with both eyes, partly with only one, with the results, as may be mentioned right away, remaining completely identical. /585

Results

With the very first experiments, I made the extremely surprising observation that astoundingly small movements can be perceived.

Closer study showed that, in ordinary daylight, with a 30 cm distance of the eye, a displacement of 0.03 mm could still be seen distinctly; one of 0.02 mm, on the other hand, could no longer be seen or was seen only with great uncertainty.

A movement of 0.03 mm corresponds to an angular displacement of circa 20 sec or a displacement of the retinal image of 1.5 μm. The change in position of the retinal image for a movement of 0.02 mm, which is no longer seen, is 1 μm.

One of my experiments will be presented in table form by way of example.

Experiment of 1 May 1906

Subject B, emmetropic. Right eye. Distance of eye 30 cm. Direction of movement vertical. The first column gives the consecutive number of the separate observations, the second the quantity of displacement in millimeters. In the third column is recorded the answer of the subject to the question whether a movement took place or not. The meaning of the last column will be discussed elsewhere.

| No. | Displacement | Perceptibility | Apparent amplitude of movement |
|---|---|---|---|
| 1 | 0,02 | yes (but not quite certain | Undetermined |
| 2 | 0,01 | No | — |
| 3 | 0,04 | Yes | 1/2 mm |
| 4 | 0,03 | Yes | 1/2 mm |
| 5 | 0,05 | Yes | 1/2 mm |
| 6 | 0,03 | Yes | Very small |
| 7 | 0,02 | No | — |
| 8 | 0,01 | No | — |
| 9 | 0,016 | No | — |
| 10 | 0,02 | Yes (very slight) | Undetermined |
| 11 | 0,03 | Yes | 1/2 mm |

As was to be expected, the results for an eye distance of 2 m were completely consistent with the above.

For this experimental arrangement, the amount of displacement which could still be detected with certainty, in average daylight, was 0.2 mm, while a movement of 0.15 mm could no longer be perceived. /586

The change in position that was to be perceived, 0.2 mm, corresponds again to a displacement on the retina of 1.5 μm.

Experiment of 23 May 1906

Subject N, myopic, corrected. Both eyes. Distance 2 m.

| No. | Displacement | Perceptibility |
|---|---|---|
| 1 | 0,1 | No |
| 2 | 0,2 | Yes |
| 3 | 0,3 | Yes |
| 4 | 0,2 | Yes |
| 5 | 0,2 | Yes |
| 6 | 0,1 | No |
| 7 | 0,1 | No |
| 8 | 0,1 | No |
| 9 | 0,2 | Yes |
| 10 | 0,18 | No |

## Visual Acuity with Regard to Movement

Evidently the image of a body must pass from one perceiving retinal element to another for us to have the impression that the body moves. If we take the cones as such retinal elements, an assumption which is justified at least for the macula lutea, then the image of a point, for the point's movement to be perceived, must first be formed on one cone, then on another.

Thus, it is evident that the amplitude of movements which can be just perceived may be utilized as a measure of visual acuity.

However, we have seen that, for a distance of 2 m, a displacement of 0.2 mm is still distinctly detected; this corresponds to a displacement of the retinal image of 1.5 μm, or to an angle of vision of circa 20 sec.

Our usual methods for determining visual acuity are based on determining how close together two points may be brought without the two impressions fusing into a single impression [2]. In this manner a much lower visual acuity is found, with the smallest angle of vision circa 50 sec to 1 min.

Thus, I found the visual acuity of my eyes with the aid of Snellen's test, under precisely the same conditions under which I had investigated movement perception. The following were the results.

At a distance of 2 m, with both eyes and also with each eye alone, I read letters 2.5 mm high. I could no longer decipher writing 2.0 mm high. The retinal image of a letter must thus have a size of 18.8 μm to be recognized. The letter was no longer read when its retinal image was only 15 μm in size. Since in these letters the thickness of each stroke and each interstice makes up one-fifth the height, accordingly two points were still perceived as separate when the distance between their retinal images was 3.8 μm, corresponding to an angle of vision of circa 50 sec. No longer perceived as separate were points with retinal images 3 μm apart, under an angle of vision of 42 sec.

Thus, one can perceive a movement between two points which at the same position in the retina are no longer distinguishable as separate.

Exner [3] already has made the same observation, but only in reference to the periphery of the visual field. He established this fact as follows. A wire, which was bent in the form of a tuning fork, supported a paperboard disk, 2 cm in diameter, on each of its two free ends. By moving the entire wire to and fro, there was first determined the least elongation for which movement was still detected; secondly, Exner separated the two disks from one another, by bending the wire, to the precise point when the two could be recognized as separate. It was shown that the elongation needed to be scarcely half as great as the distance of the two disks from each other. He remarked on the expediency of this phenomenon, since we are thereby induced to glance toward /588 the moving object.

According to my experiments, the assertion just made applies to the entire retina, including the position of clearest vision.

After concluding this series of experiments I found that Stern [4] had arrived at quite similar results with a different method. Stern fastened a paperboard screen, with a square opening 10 cm on a side, at the end of a long, dark corridor, in front of a milk-glass plate. The opening served as illuminating object. The paperboard screen could be moved sideways easily and noiselessly. The observer was 6 m 60 cm from the illuminating object, which was reduced by the objective lens of a microscope to 1/400th the natural size but, on the other hand, was moved closer to the eye. In addition, a stationary point was always visible, sometimes two. With this test apparatus, the lower limit of perceptible movement was found to be that corresponding to an angle of vision of 15 sec.

## How May One Explain the Fact that the Perception of Motion Is Finer than the Discrimination Capacity at the Same Position in The Retina?

At first glance it seems remarkable that the visual acuity is found to be much finer when we investigate it by means of minute movements than when we observe two points and see how long they are still perceived as single. This difference becomes understandable if one takes into consideration other ways of finding visual acuity. Thus Volkmann [5] could detect much greater visual acuity already in 1863.

He still clearly distinguished two spaces which were next to each other and separated by wires when the difference between them corresponded to an angle of vision of 12.4 sec.

Wülfing [6] constructed a fissure of circa 1/3 mm width /589
arranged in such a way that one could measurably displace its lower half parallel to the gap while the upper half remained still. Evidently the gap was illuminated from behind, thus forming a light line on a dark background. If the lower half of the fissure was adjusted so that it was displaced 0.1 mm with regard to the upper, this dislocation could still be detected at a distance of 2 m, or for an angle of vision of 10 sec. Wülfing was able to make similar observations with verniers, with black india ink on white cardboard.

In agreement with this, Hering [7] found a visual acuity corresponding to 11-12 sec. He united stereoscopically two groups of lines which were engraved on a glass plate at the pupillary distance. For one eye, the lines were all 1 mm apart from each other; for the other, the interval was small fractions of a millimeter greater or smaller than 1 mm.

With this apparatus, Hering found "that with favorable illumination, distances of the lines from one another corresponding to an angle of vision of 11 sec were able to effect a still definite discrimination of distance in the merging image."

Hering [8] also gave an explanation for the differences according to the method used.

If we imagine the retina as a mosaic consisting of purely regular hexagons, with each hexagon representing a visual element, it is clear that two lines or two points can only be detected as such if one hexagon remains between them. If the latter is the case, then the distance between two stimuli must be at least slightly greater than the diameter of such a hexagon; for if the distance is smaller, no visual element can remain between them, but rather two adjacent elements are stimulated, with the consequence that both stimulations coalesce, so that we do not see /590
two points, but only one.

It is otherwise, however, with the vernier-type arrangement of two lines. For these no interstice is necessary for a difference to be detected. As long as there has been no displacement of the two lines with regard to each other, we see them in a straight line, "the apparent position of which is determined by the spatial values (width values) of all visual field elements on which comes to rest the image of the line." If half the strip is now moved parallel with the strip, the difference in location is noticeable as soon as the moving part encounters another series of retinal elements, which the stationary part has not yet stimulated. One may easily be convinced that a

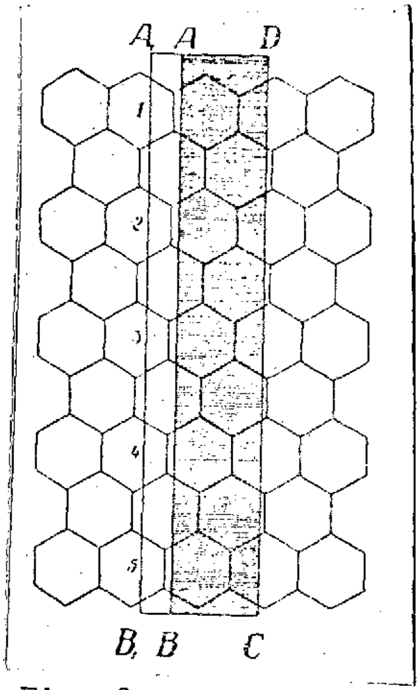


Fig. 2.

displacement of a fraction of the diameter of a hexagon suffices to set in action a new series of retinal elements.

In this way, the actual fineness of the optical space sense is found, from which Hering [9] distinguishes the "optical resolving power," which is found by determining the smallest interval between points which can still be detected as separate.

Quite similar results are found in investigations by means of movements, i.e., by means of a moving line. If we again imagine the retina as represented by a great number of hexagons, each of which corresponds to a visual element, then a band, at first considered to be at rest, forms an image on the retina in a way such as might be represented by the hatched rectangle ABCD in Fig. 2. If this band is moved slightly, then the line AB is displaced toward $A_1B_1$. The consequence of this displacement will be that now a series of quite new visual elements are stimulated, which earlier were at rest, i.e., 1, 2, 3, 4, and 5.

Evidently, however, such a stimulation of new perceiving elements in the retina, occurring at a certain time, is perceived as motion.

In this explanation, I have left completely out of consideration the fact that every point forms an image as a circle of dispersion. Thus, one sees that the phenomena that I have observed can be completely explained without considering physical irradiation. It is not disputed, however, that dispersion of light can come into consideration.

Thus, the perceptibility of movement agrees in general with the fineness of the optical space sense, but, as was emphasized above, is finer than the resolving power mentioned by Hering.

However, Stern [10], in his work which has been cited several times, comes to the conclusion that in direct vision the visual acuity is the same for motion as for rest, with visual acuity being understood as resolving power, as can be discerned from his work.

This contrast can be easily explained from the method by which Stern [11] tested visual acuity for stationary objects. In the same corridor in which he studied motion perception, he set up a large milk-glass panel, which was illuminated from behind uniformly and fairly intensely. Over this was stretched a black strip of paper in a vertical direction. If this was wide enough, one saw two fields separated by a black line. He then made the paper narrower until the point when the two light areas appeared to come together, or, in other words, to the point when the band became invisible. And, a movement which had the same displacement as the width of the just-detectable band could also be perceived. However, the recognition of a dark band on a white background has nothing to do with visual acuity [12]. It is just /592
as if one wished to draw some conclusion for visual acuity from the smallness of a perceptible point, such as a star. Thus, Stern's results signify: a movement is perceived at the place of clearest vision when its displacement is as large as a just-still-perceivable band on an illuminated background. In this form, Stern's results contain absolutely no contradiction with my findings.

## Estimation of the Amplitude of Small Movements

Among the most striking phenomena in motion perception, as I was able to observe immediately, is the fact that the small changes in location are considerably overestimated. All persons who knew nothing of the arrangement estimated the displacement as approximately 10 times its actual amount. Consequently, in all my experiments I also reported the estimated size of the movement. This is the purpose of the last column in the experiment of 1 May 1906, p. 4[illegible] One sees quite clearly that whenever any value could be given for the displacement it was estimated much too large. The movements were not so much overestimated with a distance of the observing eye of 2 m, as could be seen from the following experiment.

Experiment of 5 July 1906, 11:00 a.m.

Subject B, emmetropic. Right eye. Direction of movement vertical.

| No. | Displacement in mm | Perceptibility | Apparent quantity of movement in mm |
|---|---|---|---|
| 1 | 1,0 | Yes | 3 |
| 2 | 0,8 | Yes | 3 |
| 3 | 0,6 | Yes | 2 |
| 4 | 0,4 | Yes | 1 |
| 5 | 0,2 | Undetermined | — |
| 6 | 0,3 | Yes | 1/2 |
| 7 | 0,2 | Undetermined | — |
| 8 | 0,15 | No | — |
| 9 | 0,25 | Yes | — |
| 10 | 0,3 | Yes | 1/2—1 |
| 11 | 0,3 | Yes | 1/2—1 |

Exner [13] long ago made the interesting observation that movements appear greater at the periphery of the field of vision than at the center. According to my experiments, this overestimating of the amplitude of movement is not restricted to the periphery of the field of vision, but also occurs centrally; at least, small movements are quite considerably overestimated. /593

## Sensitivity of Various Sections of the Retina to Minute Movements

Since according to the observations of Exner which were just mentioned, a movement appears larger if it is perceived with only the peripheral parts of the retina, it would actually be expected that movements could be perceived with the periphery which are so small that we do not notice them centrally. This assumption, however, contradicts a statement of Stern. Stern [14] observed that a moving object, if it is to be detected as moving, must accomplish a movement, at a distance of 20° from the point of fixation, which is five times that which is still detected with direct vision.

I can now supplement Stern's statement by a more precise investigation of the visual field, whereby I came to the following results.

For a movement to be perceived, it must be the larger, the farther its retinal image is from the macula lutea. The amplitude for which perception passes over the threshold increases in all directions continuously outward from the macula.

This result represents a good analogy with the observation of Aubert [15], who had found that a movement, in order to be perceived, must be the more rapid the farther it is from the center of the field of vision.

Connected with this finding of Aubert appears to be the phenomenon first indicated by Czermak [16], the fact that the /594 second hand of a pocket watch appears to move forward more slowly when we look at a part of the clock which is distant from it, e.g., at the 12.

However, the sensitivity to perception of minute movements does not decrease toward the periphery uniformly in all directions.

In general it can be said that small movements in directions right and left of the fixation point are perceived very far outward in the field of vision, up to the periphery, but are perceived much less far upward and downward.

These perimetric studies could be made by fixing a certain point on the wall and producing the movement to be studied at various distances from this point. However, my apparatus on which movements were to be produced was not suited for this.

Consequently, I proceeded in the following, much simpler way. The apparatus, which was fastened to the wall, remained in its position. On the other hand, the point of fixation was changed, being made visible on the wall by a certain mark such as a drawing pen.

Thus, if a point was to be studied which is 10 cm to the right of the fixation point in the field of vision 2 m from the eye, then a point had to be fixed on which was 10 cm to the left of the movement to be investigated.

With this arrangement, whereby the movements always took place at the same location on the wall, care was also taken that the distance from the eye was always the same, i.e., 2 m. However, the same does not apply for the fixation point. For, if the latter was far from the movement to be observed, it was naturally somewhat more than 2 m from the eye. In consequence, somewhat too far an adjustment is made for the movement. The error caused by accommodation, however, appears fairly insignificant for a distance of 2 m, as I was easily able to convince myself through control experiments, at least for the horizontal direction of the field of vision. For this purpose, I fastened the fixation sign, at a height of 1.28 m above the floor, on a stand which I could set up at the desired location, right or left /595 of the movement, so that the distance from the eye remained always 2 m. With this arrangement as well, the results were the same.

It can best be seen how the various parts of the retina behave with regard to their sensitivity to small movements from the subsequent table.

In this table, the first column shows the location of the fixation point with reference to the movement studied. The distances are expressed in centimeters. In the second column are the distances given in angles of vision, rounded off to half a degree. The third and fourth columns present the smallest movements seen at the particular location in the eye, with the third column giving the quantity of displacement as a distance in millimeters, the fourth in angle of vision. In the same way, the displacements that are no longer perceived are presented in the fifth and sixth columns.

<u>Summary Survey of Experiment of 7 June 1906, 10:00 a.m.</u>

Subject N., myopic, corrected. Right eye. Room illumination quite bright.

| Fixation point with reference to moving object (mo) | Distance of fixation point from mo in angles of vision, nearest 1/2° | Perceived | | Not perceived | |
|---|---|---|---|---|---|
| | | in mm | in angle of vision | in mm | in angles of vision |
| Moving object (mo) | 0 | 0,2 | 20,6 sec | 0.15 | 15.45 sec |
| 13 cm right of mo | 3.5 | 0,2 | 20,6 sec | 0.15 | 15,45 sec |
| 13 cm left of mo | 3.5 | 0,2 | 20.6 sec | 0,15 | 15,45 sec |
| 13 cm above mo | 3,5 | 0,4 | 41,2 sec | 0,3 | 30,9 sec |
| 13 cm below mo | 3.5 | 0,5 | 51,5 sec | 0,4 | 41,2 sec |
| 26 cm right of mo | 7.5 | 0,5 | 51,5 sec | 0,4 | 41,2 sec |
| 26 cm left of mo | 7.5 | 0,7 | 1 Min. 12,1 sec | 0,5 | 51,5 sec |
| 26 cm above mo | 7.5 | 1,0 | 1 Min. 43 sec | 0,9 | 1 Min. 32,7 sec |
| 26 cm below mo | 7.5 | 1,5 | 2 Min. 34,5 sec | 1,4 | 2 Min. 24.2 sec |
| 46 cm right of mo | 13.0 | 1,2 | 2 Min. 3,6 sec | 1,0 | 1 Min. 43 sec |
| 46 cm left of mo | 13,0 | Blind spot | | | |
| 46 cm above mo | 13,0 | 3,0 | 5 Min. 9 sec | 2,5 | 4 Min. 17,5 sec |
| 46 cm below mo | 13.0 | 3,0 | 5 Min. 9 sec | 2,5 | 4 Min. 17,5 sec |
| 66 cm right of mo | 18,5 | 1,4 | 2 Min. 24,2 sec | 1,3 | 2 Min. 13,9 sec |
| 66 cm left of mo | 18.5 | Blind spot | | | |
| 66 cm above mo | 18,5 | | | 6,0 | 10 Min. 18 sec |
| 66 cm below mo | 18.5 | | | 6,0 | 10 Min. 18 sec |
| 100 cm right of mo | 26,5 | 1,5 | 2 Min. 34,5 sec | 1,4 | 2 Min. 24,2 sec |
| 100 cm left of mo | 26,5 | 1,7 | 2 Min. 55,1 sec | 1,5 | 2 Min. 34,5 sec |
| 100 cm above mo | 26,5 | | | 6,0 | 10 Min. 18 sec |
| 100 cm below mo | 26,5 | | | 6,0 | 10 Min. 18 sec |

The relationships can best be clarified through a graphic presentation, as is usual in perimetry.

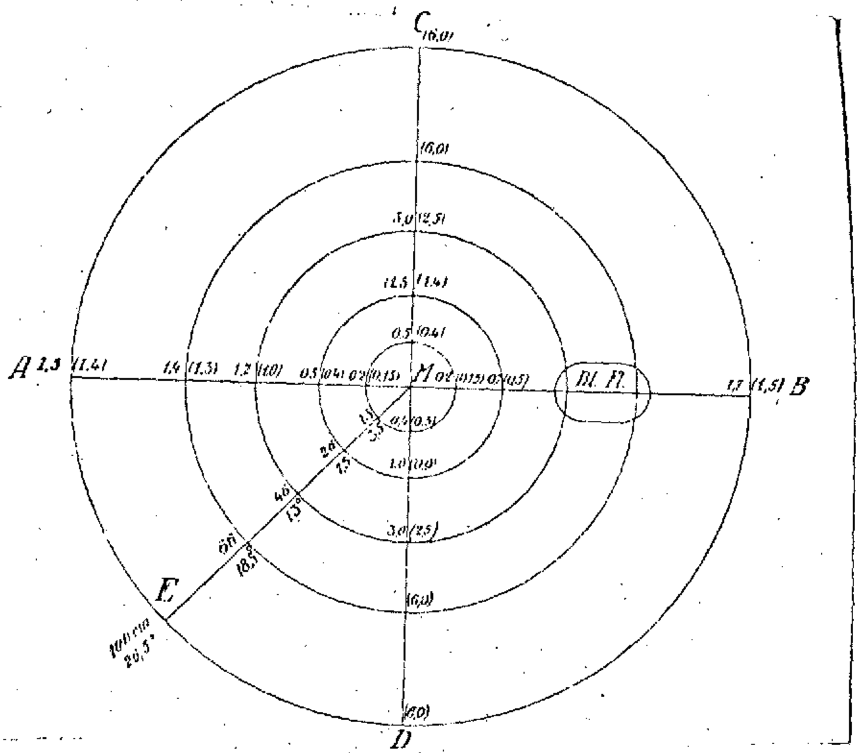


Fig. 3. Field of vision of right eye for a distance of 2 m. The circles which are concentric around the point of fixation M correspond to visual angles of 3.5, 7.5, 13, 18.5, and 26.5 degrees. These quantities are designated along an oblique line EM. The numbers above this line signify the radii of the circles in centimeters, projected onto the wall which is 2 m from the eye. The numbers on the horizontal (AB) and vertical (CD) diameters of the circle give the perceptible displacement at the particular location in the field of vision (expressed in millimeters). The numbers enclosed in parentheses represent displacements which are no longer perceptible. The oblong Bl. Fl. which is drawn on the right horizontal radius MB schematically represents the projection of the blind spot.

Without going into more detail concerning the extensive literature about indirect visual acuity, I might take the following information, for comparison purposes, from a work of Wertheim [17]. This information corresponds in essentials with the results of Aubert and Förster [18].

Visual acuity decreases more rapidly upward and downward than /597 it does toward the right and toward the left, more rapidly upward than downward, and more rapidly medially than laterally.

Concerning visual acuity with regard to motion, as we have seen, something quite similar can be observed, in that with increasing distance upward or downward from the fixation point the displacement must increase much more rapidly in order still to be seen than with increasing distance to the right or the left. On the other hand, in my investigations of motion perception, I was able to observe no significant difference between medial and lateral, on the one hand, and above and below, on the other hand.

With passage onto the blind spot, the perception of movements does not suddenly cease, but rather the sensitivity gradually becomes less and less, so that the farther one goes into the area of the blind spot, the larger the movements must be in order to be detected.

Dependence of Sensation of Small Movements on Their Speed

An essential criterion for perception of minute movements proved to be the speed with which the displacement was made. According to Aubert's studies [19], according to which a movement is more easily perceived if it takes place rapidly, it was to be expected that the smaller is a displacement, the more rapid it must be to be detected. This expectation could be confirmed in numerous cases. Although I did not make any thorough investigations in this regard, I could frequently observe that a movement was not noticed if the lever was moved relatively slowly, while if the lever was moved more rapidly, for the same amount of displacement, then the movement was definitely recognized.

Consequently, in order to obtain the most comparable results, the speed of all tests would have to remain the same. This was obtained fairly satisfactorily by undertaking to perform the displacement as rapidly as possible.

To obtain an idea of how rapidly the movements took place /598
in my tests, I recorded the displacements by means of the Marey method of transmission of air on a rotating kymograph drum. It was shown that for a displacement of 2mm a time of 1/5 sec was required for each movement back and forth. The time of a single displacement was 1/15 sec.

Of course, I am unable to say whether this speed is precisely the most favorable for motion perception, since I have not yet undertaken any systematic studies of the relation between speed and perceptibility of a movement.

With the result that a rapid movement is more easily detected than a slow one, I am somewhat in contradiction with Stern [20], who found that the slowest movements are best recognized.

Perhaps this contradiction can be explained by the fact that Stern always worked with a comparison light as stationary point, frequently even with two, while in my studies I never had a stationary point. Thus, it is easily conceivable that if the object moves too slowly one is perhaps inclined to follow the movement with the eye, but one loses the ability to judge where the image of the object was before the movements took place.

Aubert [21] found that in complete darkness, where reference objects also were absent, even movements with a large excursion and a fairly significant speed can scarcely be detected. Stern also made this observation [22]. Bourdon [23], however, came to the view that Aubert's assertion was exaggerated.

Although I did not work in darkness, in my test apparatus I nowhere had a stationary point which I could compare directly with the moving strip. Nevertheless, if the displacement was sufficient for perception at all, I was able to say quite definitely /599 whether a movement had been made or not.

I am unable to decide on what basis this certainty of judgment rests in my experiments. Perhaps it is a consequence of the eye seeing some objects, even if only peripherally, which it could use as a reference point. I have not yet set up tests in darkness.

Dependence of Motion Sensation on Total Illumination

In my investigations I observed that the threshold of sensation is quite considerably affected by variations in lighting. Within certain limits, the lighter it is the smaller the changes in location are that can be still perceived. This effect of total lighting applied more to indirect vision than to direct.

In direct vision, the lower limit of perceived movement varied between 0.2 and 0.3 mm, for a distance of the eye of 2 m. If one's glance was only slightly turned aside (corresponding to an angle of vision of 3.5 degrees), this limit was between 0.2 and 0.7 mm. Expressed as angle of vision, these smallest perceivable displacements, for two different lighting conditions, were circa 20 and 30 sec for the macula lutea. In indirect vision, i.e. with an angular distance of the movements of 3.5 degrees, the smallest perceivable displacements were circa 20 sec and 1 min 12 sec. An example is provided through comparing the following experiment with that reported on p. 15.

Experiment of 31 May 1906

Subject N, myopic, corrected. Right eye. Dusky weather.

| No. | Fixation point with regard to moving object (mo) | Distance of fixation point in degrees | Displacement in mm | Perceptibility |
|---|---|---|---|---|
| 1 | 13 cm left of mo | 3,5 | 0,15 | No |
| 2 | 13 cm left of mo | 3,5 | 0,2 | No |
| 3 | 13 cm left of mo | 3,5 | 0,5 | No |
| 4 | 13 cm left of mo | 3,5 | 0,7 | No |
| 5 | Moving object | 0 | 0,2 | No |
| 6 | Moving object | 0 | 0,3 | Yes |
| 7 | Moving object | 0 | 0,3 | Yes |
| 8 | Moving object | 0 | 0,2 | No |
| 9 | Moving object | 0 | 0,2 | No |
| 10 | 13 cm left of mo | 3,5 | 0,8 | Yes |
| 11 | 13 cm left of mo | 3,5 | 0,7 | No |
| 12 | 13 cm left of mo | 3,5 | 0,8 | Yes |
| 13 | 13 cm left of mo | 3,5 | 0,8 | Yes |
| 14 | 13 cm left of mo | 3,5 | 0,7 | Yes |
| 15 | 13 cm left of mo | 3,5 | 0,7 | Yes |
| 16 | 13 cm left of mo | 3,5 | 0,6 | No |
| 17 | 13 cm left of mo | 3,5 | 0,7 | Yes |
| 18 | 13 cm left of mo | 3,5 | 0,6 | No |
| 19 | 13 cm left of mo | 3,5 | 0,7 | Yes |

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In the same way, the field of vision 13 cm from the point of fixation, toward the other side, was also investigated, with a displacement of 0.7 mm being perceived, one of 0.6 mm no longer perceptible.

Direction of Movement

All results given hitherto were obtained from studies in which the movement took place in the direction from above downward; i.e. the paper strip which was visible below the gap in my apparatus had a horizontal position and could be moved in a vertical direction.

My studies convinced me that that there is no difference in the results whether the movement takes place in a vertical or a horizontal direction. However, detailed studies concerning sensitivity to motion in a horizontal direction must be delayed for a later report, since hitherto, for technical reasons, no direct studies have been undertaken comparing horizontal and vertical movement, as is of course necessary.

Summary of Results

For the sake of clarity, the results of the present study will be summarized again briefly.

1. At the location of clearest vision, we are able to perceive a displacement the size of which corresponds to an angle of vision of circa 20 sec, or to a displacement on the back of the eye of 1.5 μm, or half the diameter of a cone inner segment.

2. Since in general two points can only be perceived as separated if the distance between them is equal to an angle of vision of 50 sec, or 3.5 μm on the back of the eye, evidently we detect a movement with the macula lutea which takes place between two points that are no longer distinguished as separate. /601

3. The small movements were considerably overestimated in my experiments, especially when the moving object was only a slight distance from the eye (30 cm), as compared to when it was 2 m from the eye. Large movements, as Exner's studies also show, are overestimated only in indirect vision, being judged correctly in the center.

4. The smallest displacement of an object which was seen was perceived with the macula lutea. Toward the periphery, the displacement had to be much greater to produce sensation of movement. The threshold increased most rapidly in the direction from below upward, increasing much more slowly in the horizontal line to the right or to the left.

5. It was generally shown that sensitivity to motion depended on the speed of the movement, in such a way that a small movement could be more easily detected with a rapid displacement than with a slow one.

6. The total lighting also had an effect, since smaller movements could be more definitely detected with bright light than with darker lighting. However, there was a certain contrast between the central and peripheral parts of the retina, since the difference in lighting had a much greater effect in the periphery than in the center.

7. These results were obtained for a movement in a vertical direction, but essentially the same was found for horizontal displacements.

## REFERENCES


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